Swift Catching gamma ray bursts on the fly . . .

Early On-Orbit Operation of the Loop Heat Pipe System on the Swift BAT Instrument

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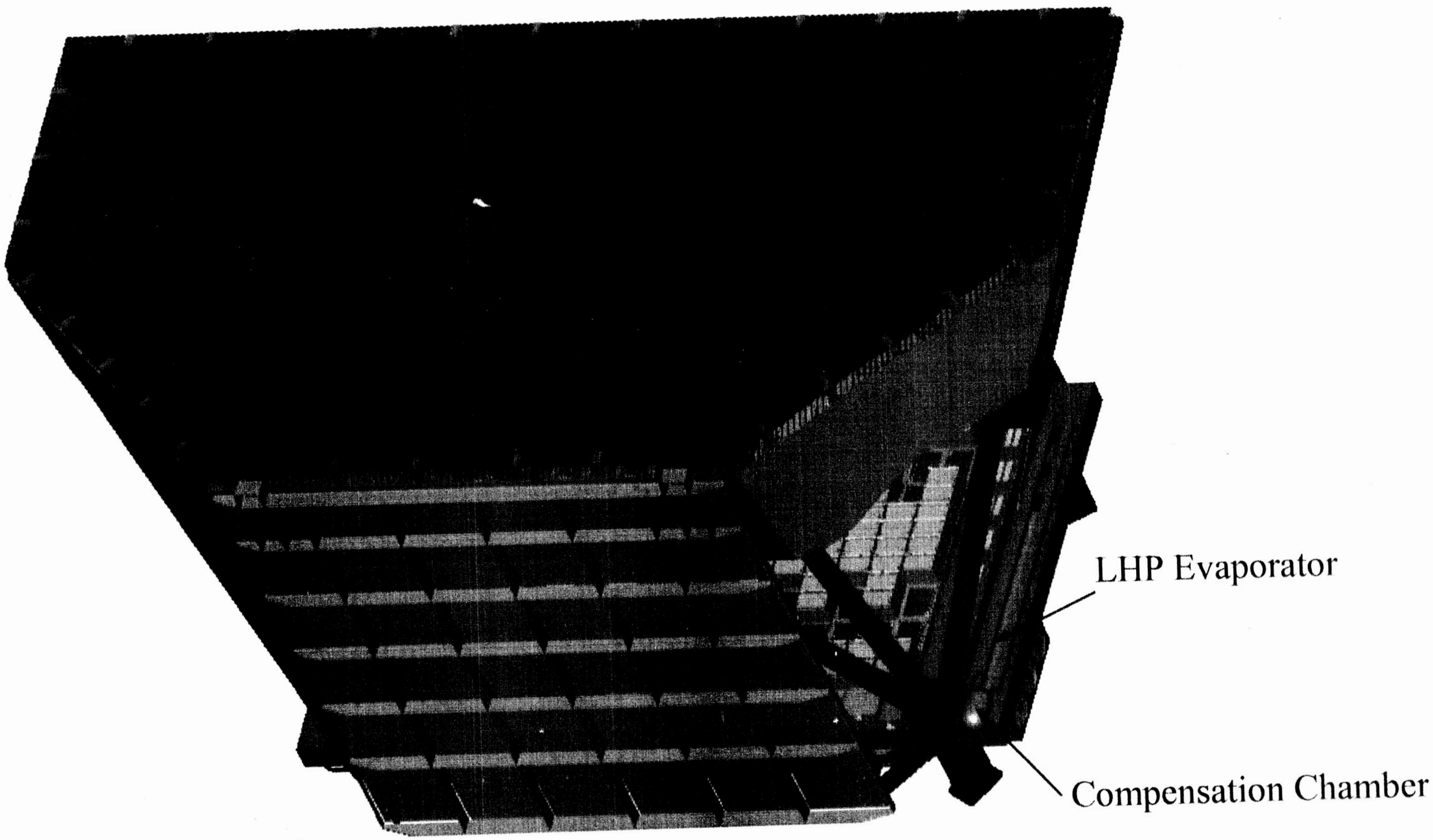
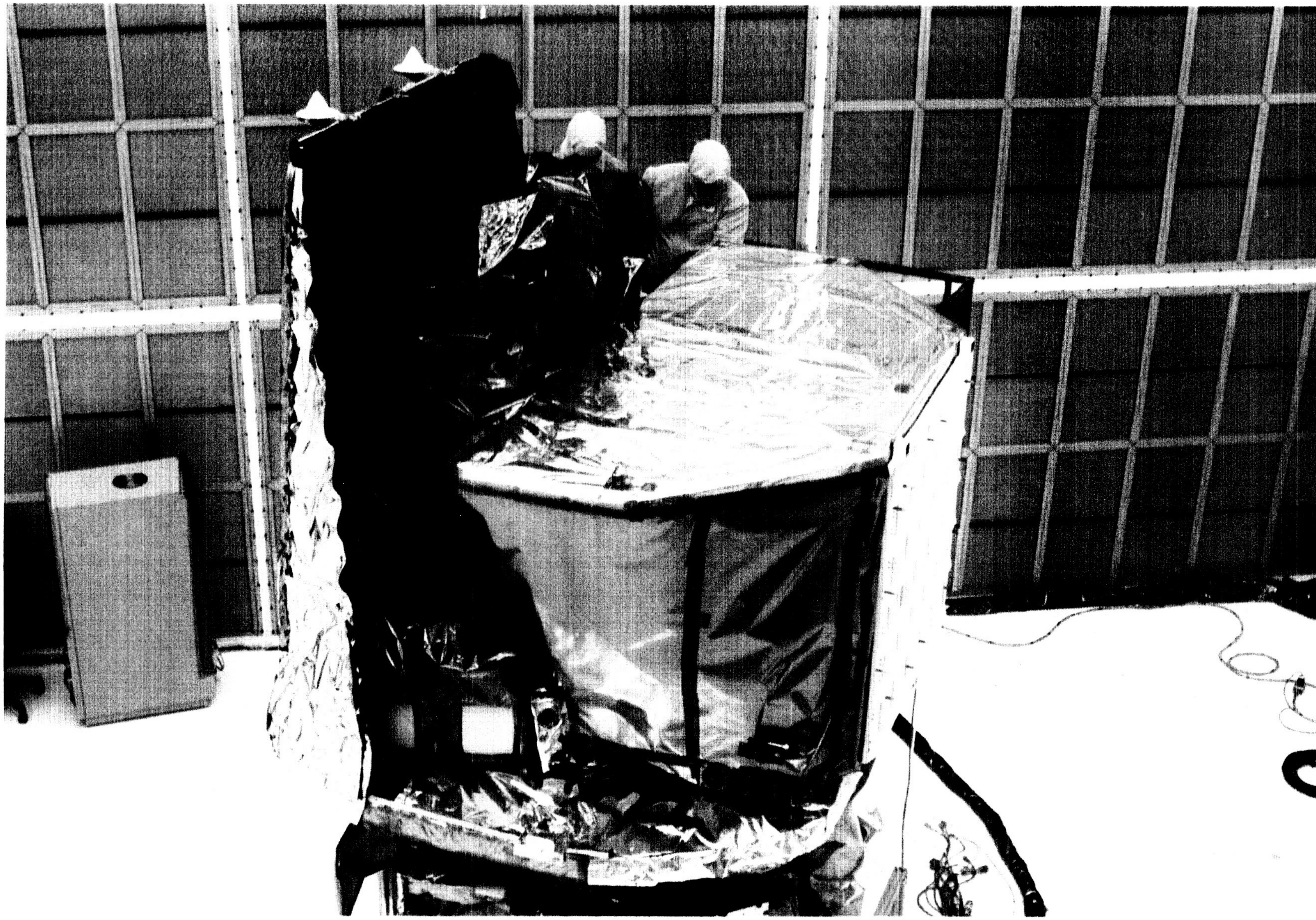
Background

- The Burst Alert Telescope (BAT) is one of three instruments on the Swift satellite
- Array of detector modules on BAT locate Gamma Ray Bursts
- Detector modules, grouped into 16 “blocks”, mounted to Detector Array Plate (DAP)
- DAP contains 8 constant conductance heat pipes which transfer instrument heat to edges of DAP
- Two Loop Heat Pipes (LHP’s), one at either side of DAP, transfer heat to common radiator for rejection to space

Burst Alert Telescope





Thermal Requirements

- Maintain detectors at constant temperature ± 0.5 °C over entire surface and over any time
  - Goal is to maintain detectors at 20 °C during flight
  - LHP nominal control temperature is +9 °C, but this can be varied in flight
  - must maintain temperature over wide range of environmental conditions
- Operating power initially limited to 15 W per loop
- Each loop is designed to transport entire heat load (253 W), but nominal operating procedure is to run both loops at all times (127 W each)
- Loop must shut down in survival mode with no more than 15 W of power
  - thermally de-couple radiator and DAP to lower survival heater requirements

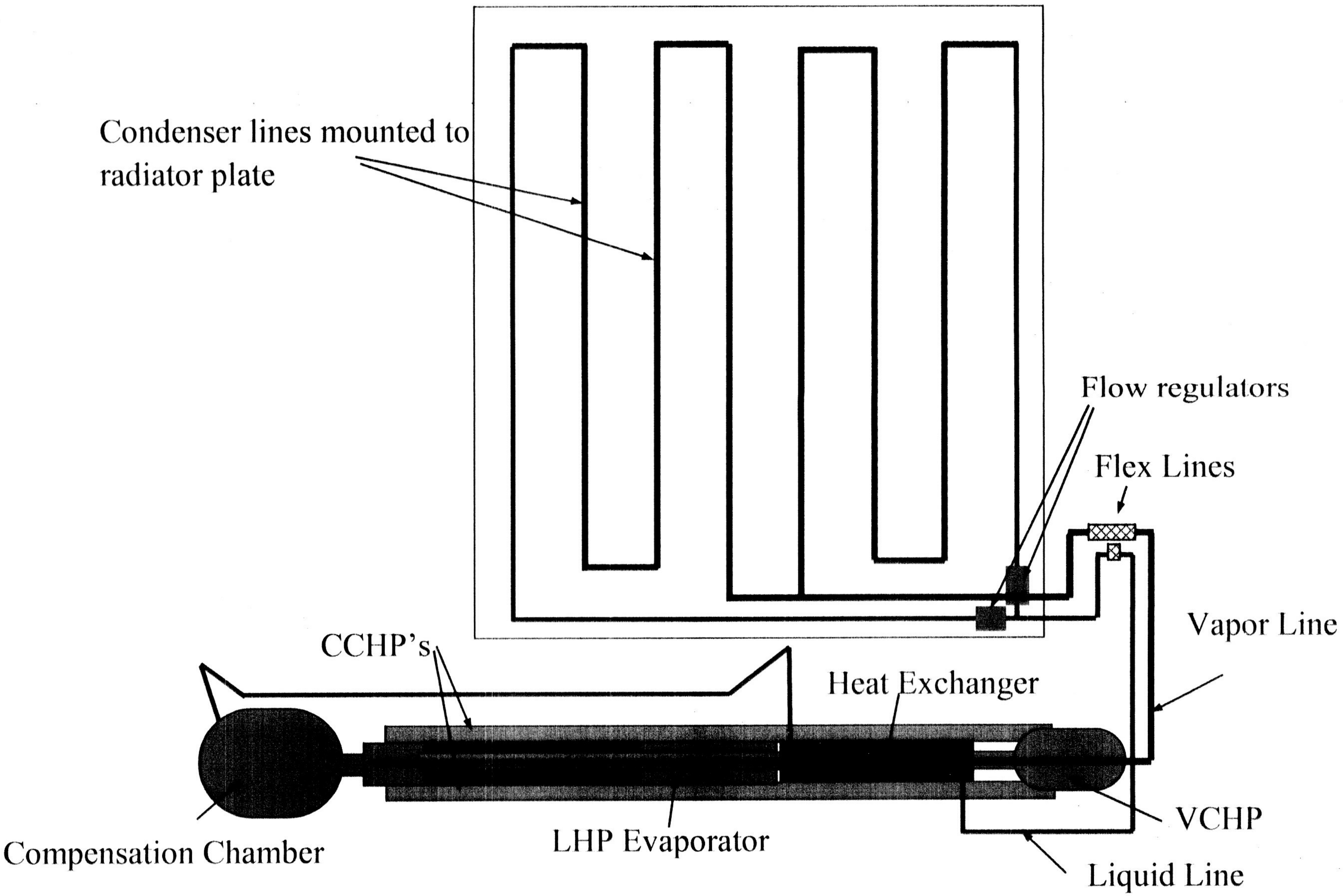
Temperature Control

- Three stages for temperature control:
  - VCHP to liquid line heat exchanger provides rough control of LHP system
    - VCHP is used to control temperature of LHP liquid exiting the heat exchanger
    - Heat transfer from evaporator to liquid line reduces liquid line subcooling to a level that can be controlled by compensation chamber heaters
  - Compensation chamber heaters provide fine control of LHP system
    - Control heaters mounted on CC provide remaining power needed to maintain set temperature
    - CC heaters are controlled using feedback thermistors mounted on CC
  - Temperature controlled heaters on DAP are used to control local gradients on plate (referred to as DAP operating heaters – two circuits with a total of 30 W)

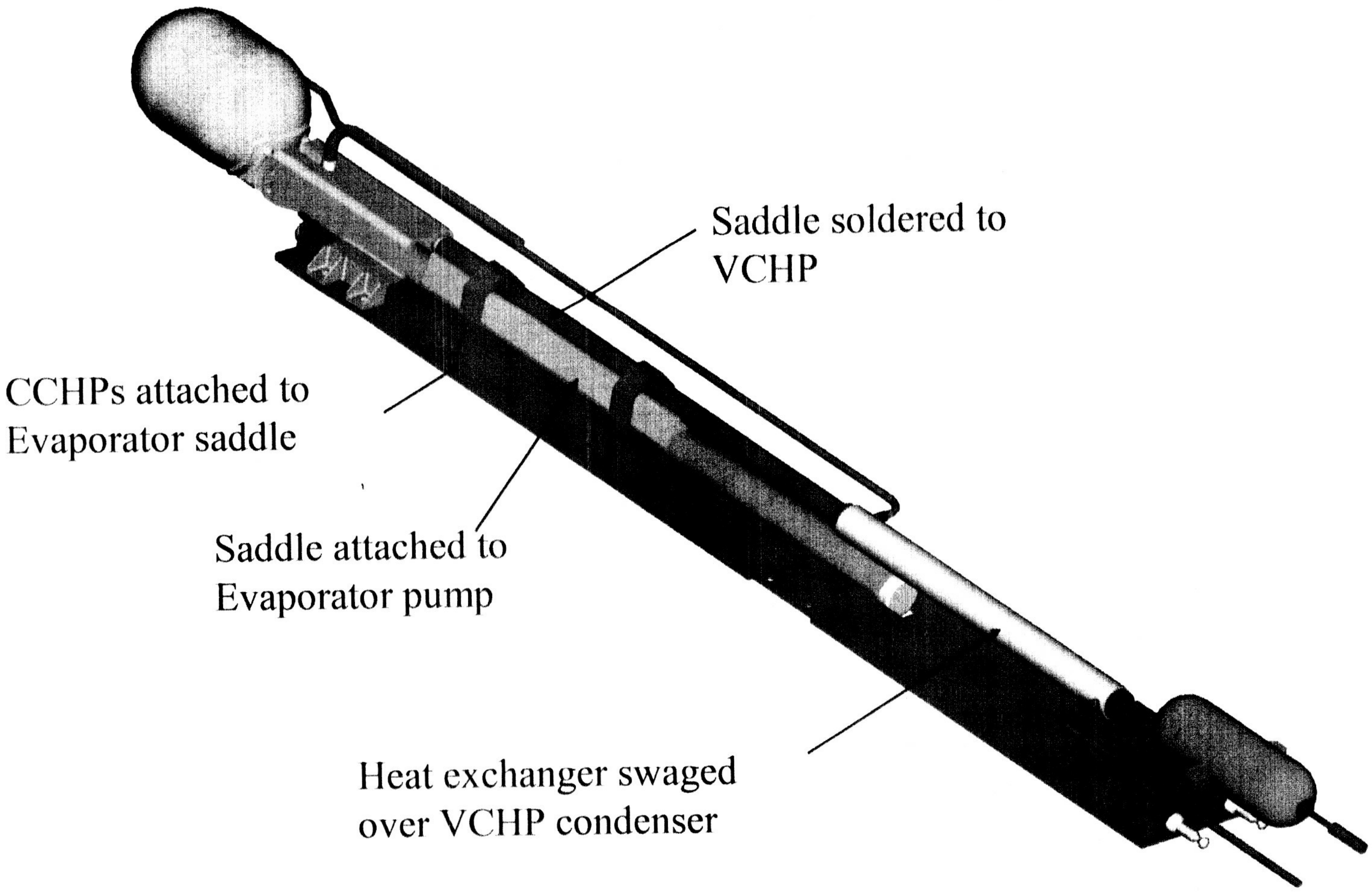
LHP Assembly

- Each LHP assembly consists of following items:
  - Single Propylene Loop Heat Pipe with two parallel condensers and associated flow regulators
  - Variable Conductance Heat Pipe (VCHP)
    - VCHP evaporator connected to LHP evaporator through a saddle
    - VCHP condenser is inner part of heat exchanger - outer sleeve of heat exchanger is part of the LHP liquid return line
  - Two Constant Conductance Heat Pipes (CCHPs)
    - Transfer heat to the LHP Evaporator from the BAT Detector Array Plate
  - Condenser lines mounted to radiator plate
    - Single radiator plate with interwoven condenser lines from both LHP assemblies

LHP Schematic (Loop 1)



Evaporator Assembly



BAT LHP Assembly Heaters

Component / Type	Number of Heater Circuits	Nominal Power (W) @ 28 V	Control Method
Compensation Chamber / Survival Heater	2*	16	In line thermostat - Primary close at -8 °C, open at -3 °C; secondary close at -13 °C open at -7 °C
Compensation Chamber / Operational Control	4^	8	Pulse Width Modulated temperature controller with user defined set point
VCHP / Control	2*	5	Feedback temperature controller, set point defined as an offset from the CC set point. Feedback is a thermistor on the liquid line exit from the heat exchanger
Evaporator Starter Heater	2*	60	commanded on/off with over-temperature safety thermostat

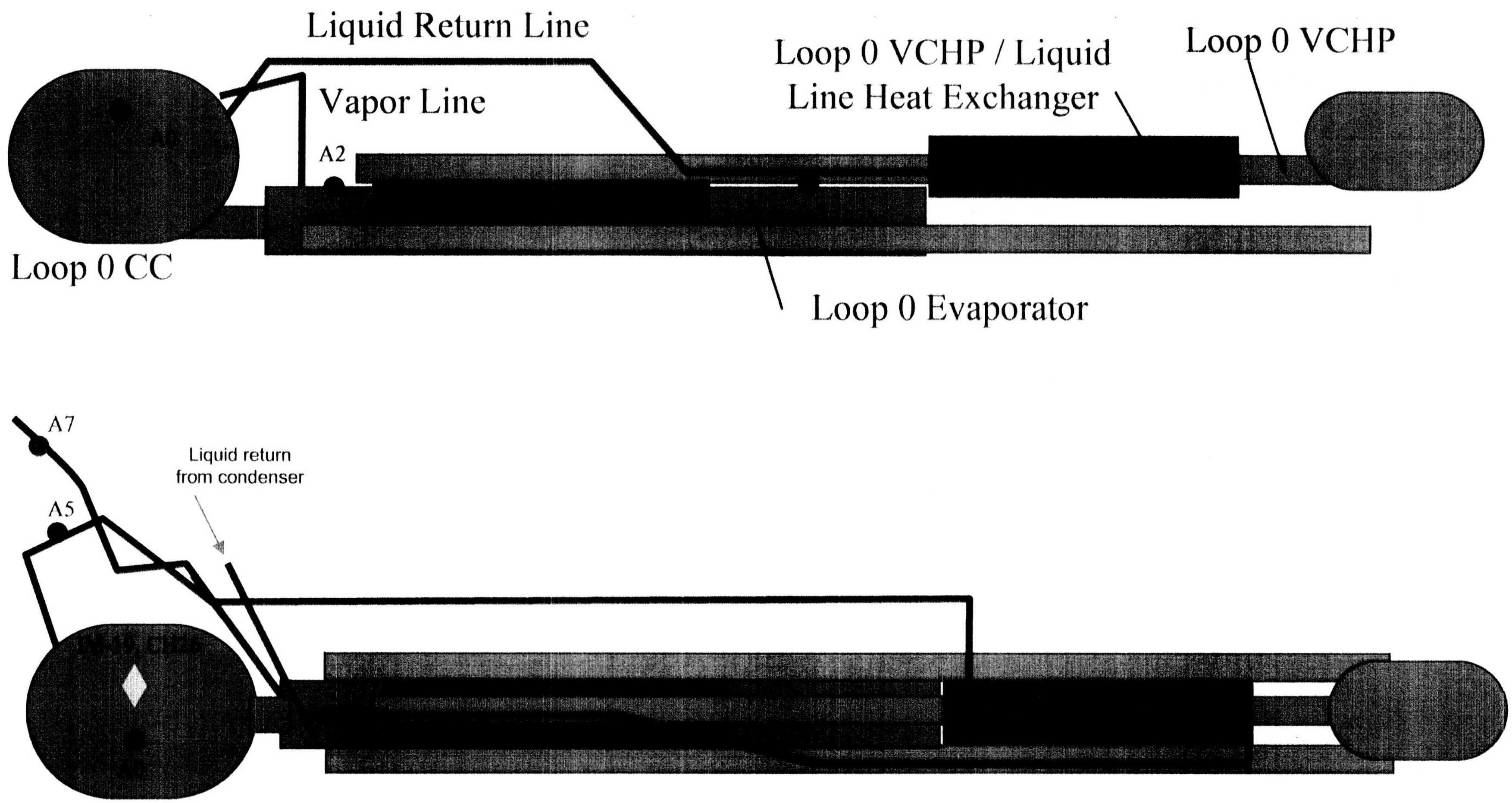
* Primary and Redundant

^ Two Primary and Two Redundant

Flight Instrumentation

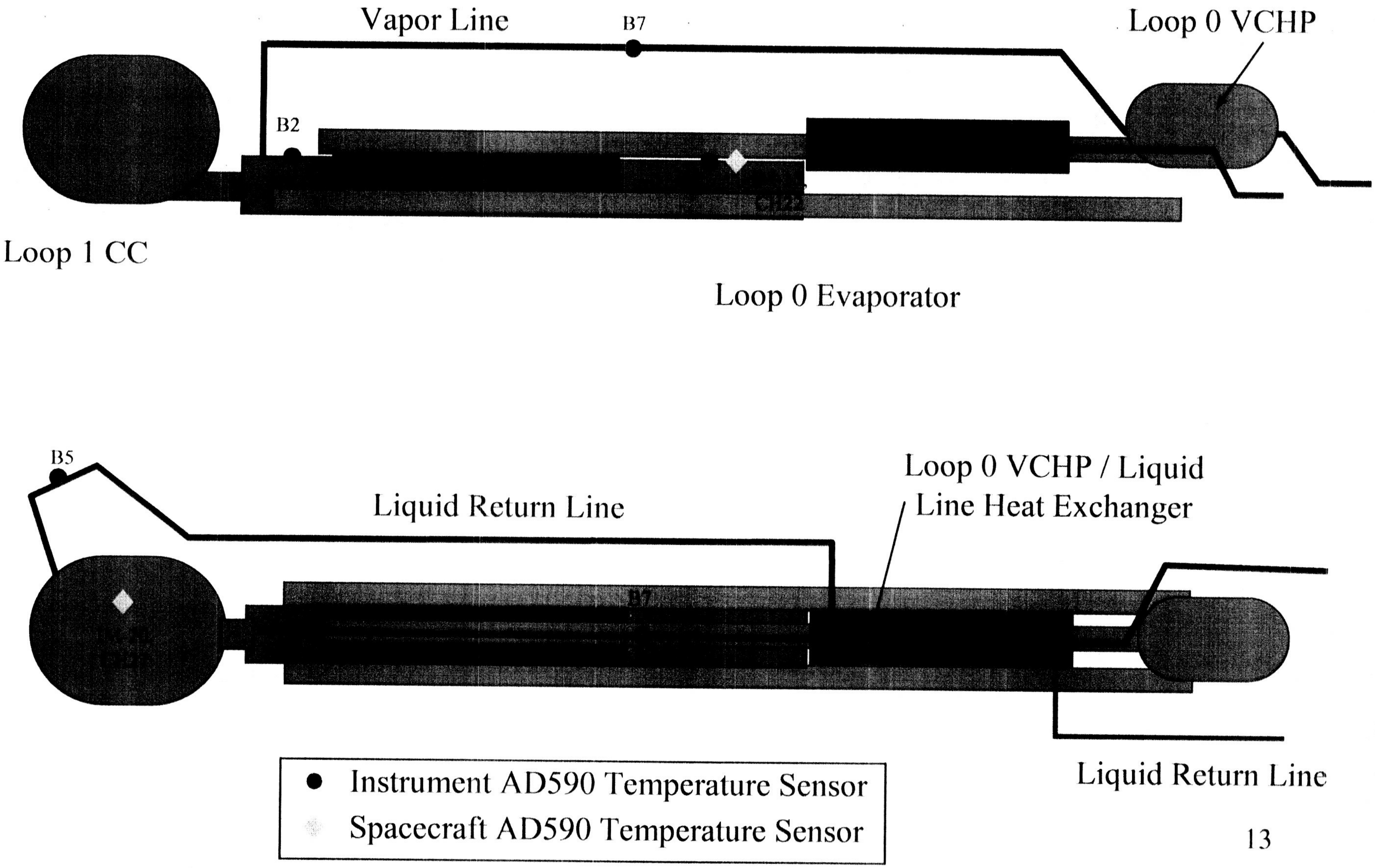
- All downlinked temperature data from AD590 temperature sensors
  - 6 spacecraft level sensors available at all times (in history data)
  - 19 instrument level sensors available only when BAT instrument electronics is powered on
  - Instrument level sensors read only to -72 °C
- CC and VCHP heaters controlled with pulse width modulated controllers which use thermistors for feedback sensors (thermistor data is not downlinked)

AD590 Locations, Loop 0 (+Y)

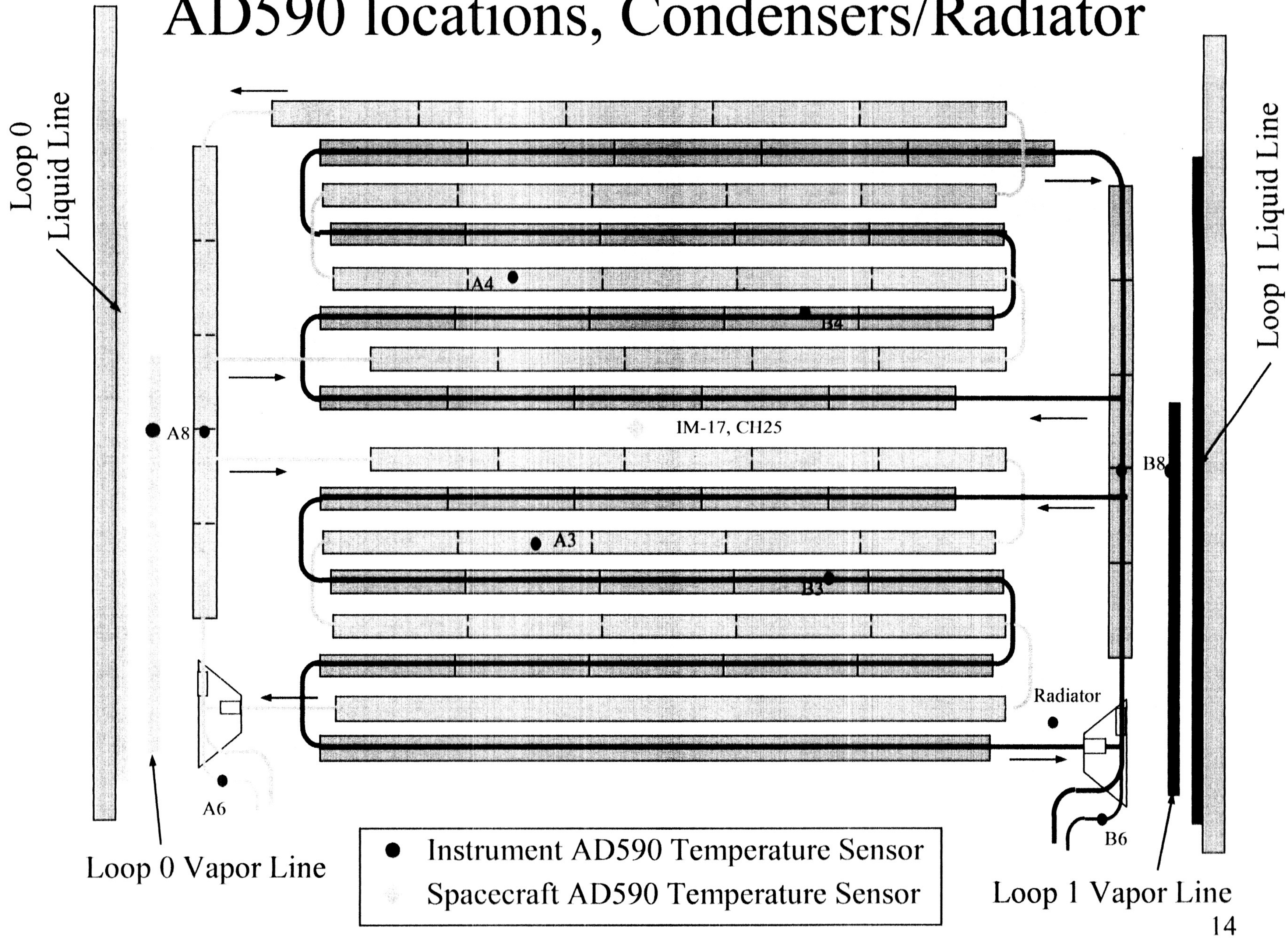


- Instrument AD590 Temperature Sensor
- Spacecraft AD590 Temperature Sensor

AD590 locations, Loop 1 (-Y)



AD590 locations, Condensers/Radiator

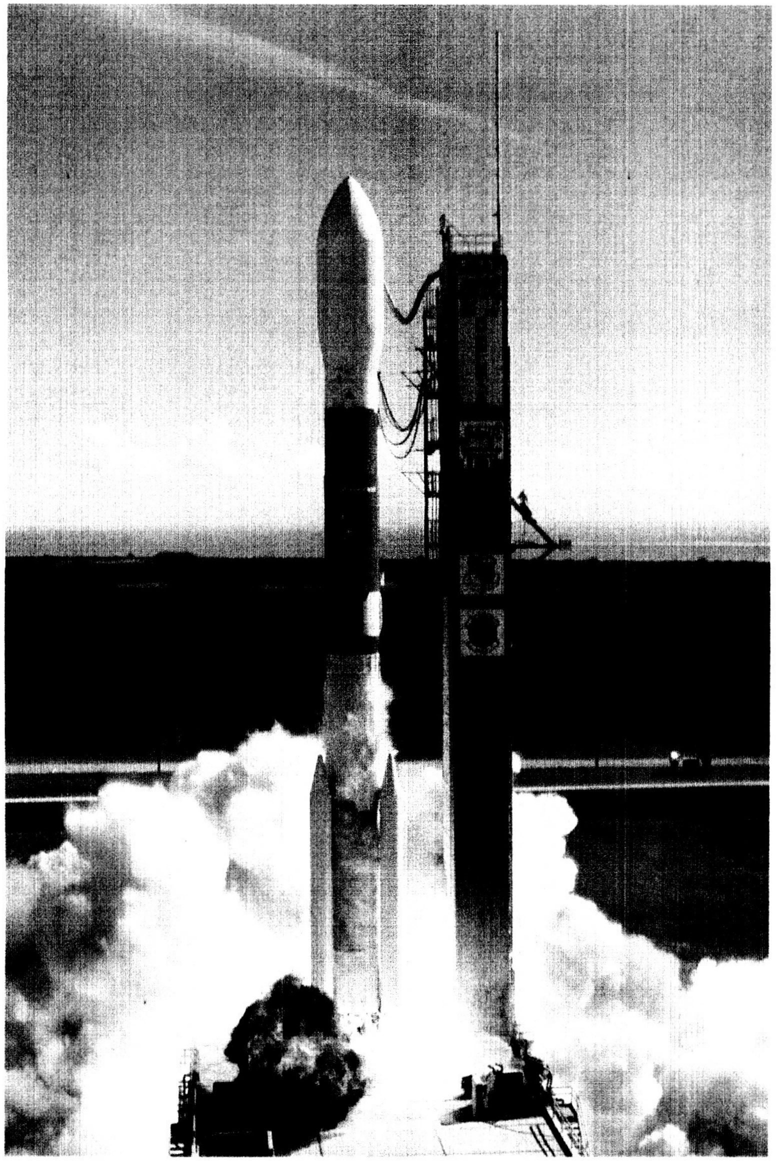


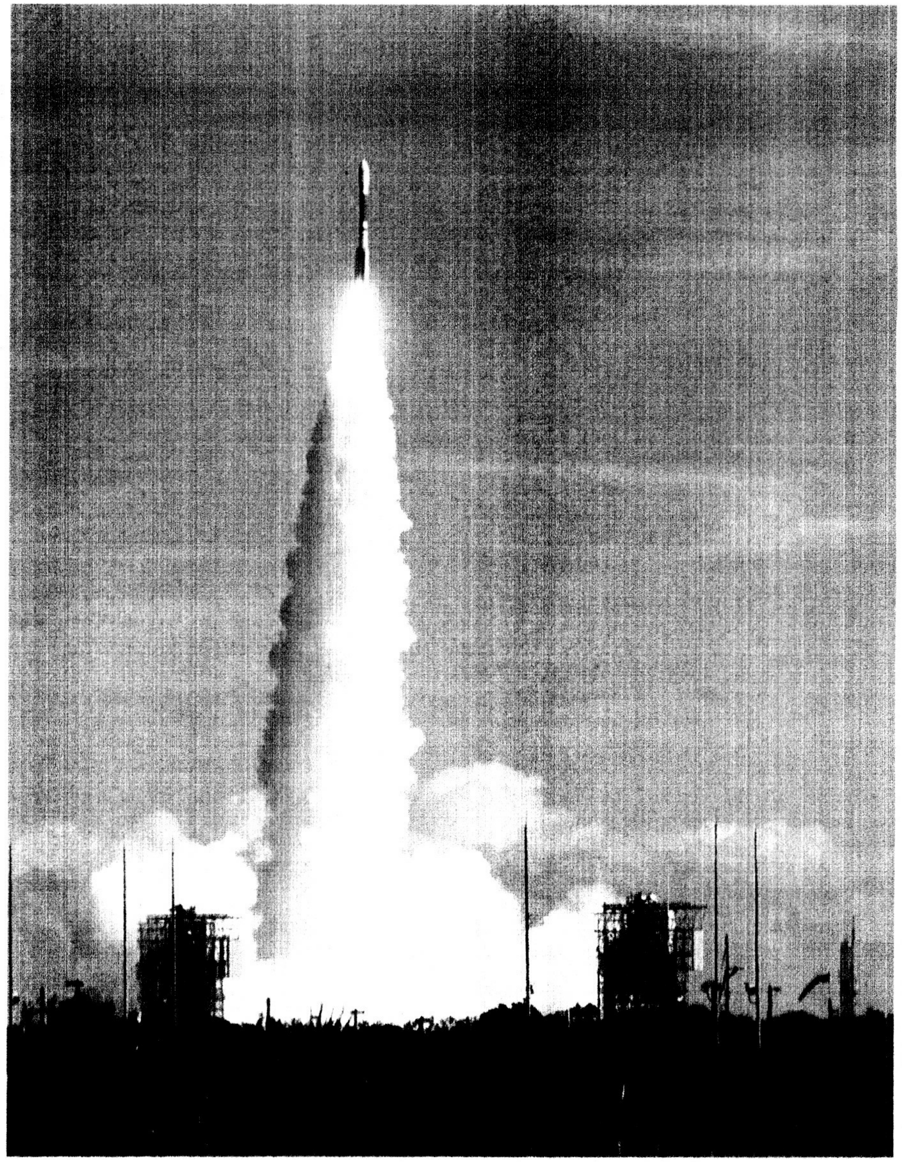
Temperature Control Implementation

- One controller controls both CC heaters and the VCHP heater
- A single set point is given to the controller; the VCHP set point is automatically set a fixed offset below the entered set point (5 °C below at a CC set point of 5 °C)
  - due to the implementation method, offset is not constant
  - offset is larger at colder set points and smaller at higher set points
- Feedback sensor for VCHP control is on the LHP liquid line at the outlet from the liquid line/VCHP heat exchanger
- When feedback sensor is above the VCHP set point, the VCHP gas reservoir heater is turned ON to shut down the VCHP and preserve the subcooling that is available
- When feedback sensor is below the VCHP set point, the VCHP gas reservoir heater is turned OFF to allow the VCHP to operate and thus transfer heat directly from the evaporator to the liquid return line

Swift/BAT Early Orbit Events

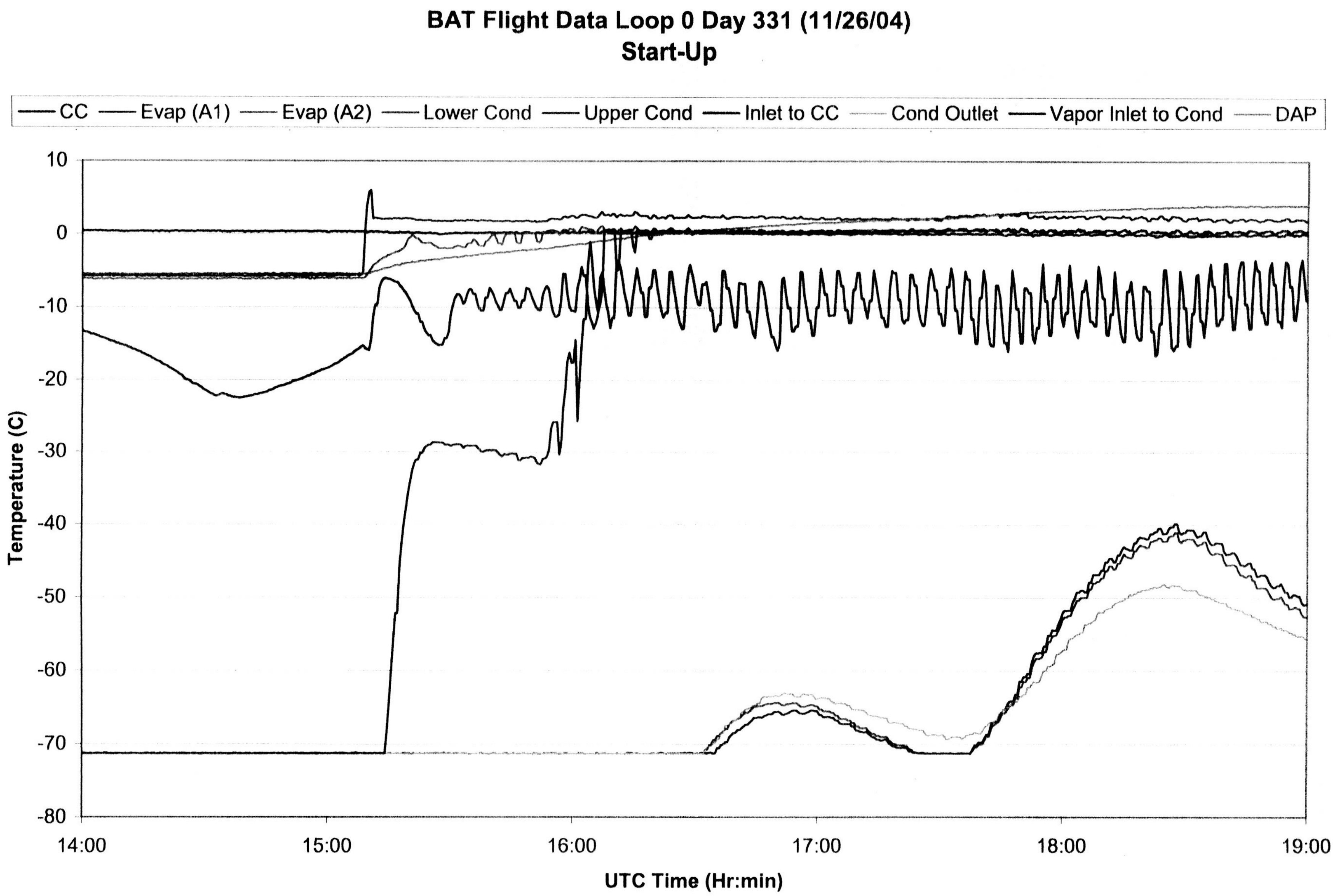
- Launch – November 20, 2004 (Day 325)
  - On Delta rocket from Cape Canaveral
- BAT Instrument remained in survival mode until 11/26 (Day 331)
- Loop 0 LHP started on 11/26
- First detector block (approximately 12 W) activated on 11/27
- Additional blocks activated on 12/1, 12/2, 12/3, and 12/8
- Loop 1 and last four blocks activated on 12/10/2004
- Saturation temperature (set point) of both LHP's raised from 0 C to 8.5 C over two days beginning on 12/11
- System conditions have been unchanged since 12/12/2004





Loop 0 Start-Up

- Prior to start-up, primary survival heaters on both CCs had been cycling (between -8 and -3 °C) – loops were not operating
- Loop 0 CC heater set to 0 °C. Loop 1 CC heater set to 10 °C to maintain Loop 1 off. System remained in this configuration for approximately 7 hours.
- DAP operating heaters (about 30 W total) turned full on (set point of 9.5 °C), Loop 0 evaporator starter heater power (60 W) activated, waited for loop to start. (No detector block powered up at this time.)
- Vapor generated in evaporator within 4 minutes of starter heater activation, superheat near starter heater of approximately 4 °C
- Due to significant thermal mass, vapor didn't reach condenser until about 1 hour after power was applied

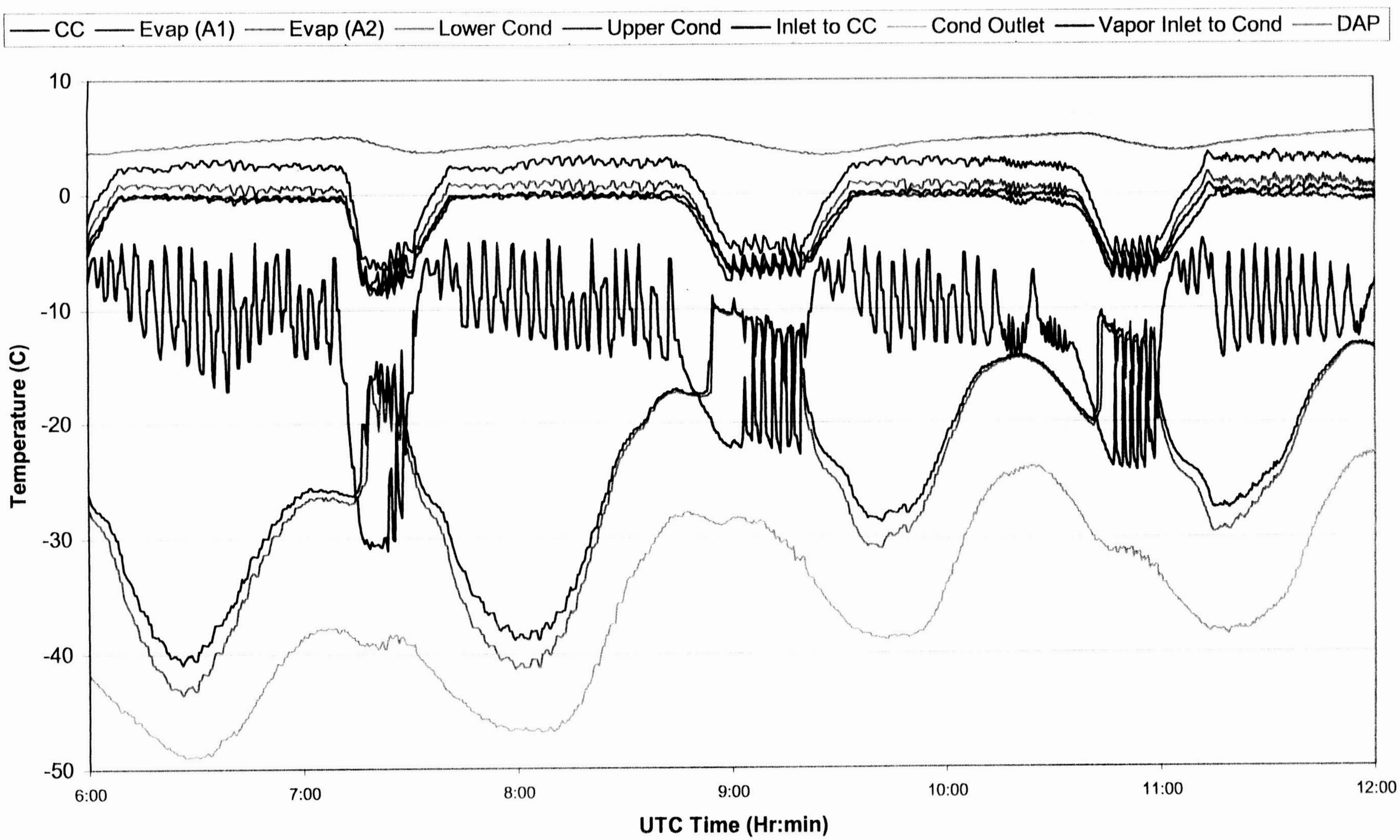


BAT Flight Data Loop 0 Day 331 (11/26/04)
Start-Up
CC
Evap (A1)
Evap (A2)
Lower Cond
Upper Cond
Inlet to CC
Cond Outlet
Vapor Inlet to Cond
DAP
Temperature (C)
10
0
-10
-20
-30
-40
-50
-60
-70
-80
14:00
15:00
16:00
17:00
18:00
19:00
UTC Time (Hr:min)

Loop 0 Cold Shocks

- As DAP temperature approached steady state after Loop 0 start-up, loop began to cold shock.
  - Cold liquid into the CC lowers saturation temperature faster than CC/VCHP temperature control combination can adjust
  - As saturation temperature decreases, effective power into the system (due to large thermal mass) increases, which in turn increases flow of cold liquid back to CC (and continues to lower saturation temperature)
  - CC temperature drops rapidly to the survival heater thermostat level, at which point survival heater cycles on
  - Additional heat into CC stops temperature decline, but CC power is not sufficient (with survival heater cycling) to return to set point until VCHP is fully operational and subcooling into CC is greatly reduced
    - VCHP reservoir is slow to respond because only cooling is through relatively small radiative coupling to space
- Cause of initial cold liquid slug into CC is difficult to determine with existing instrumentation. Some combination of varying radiator environment, and condenser tubing routing likely.

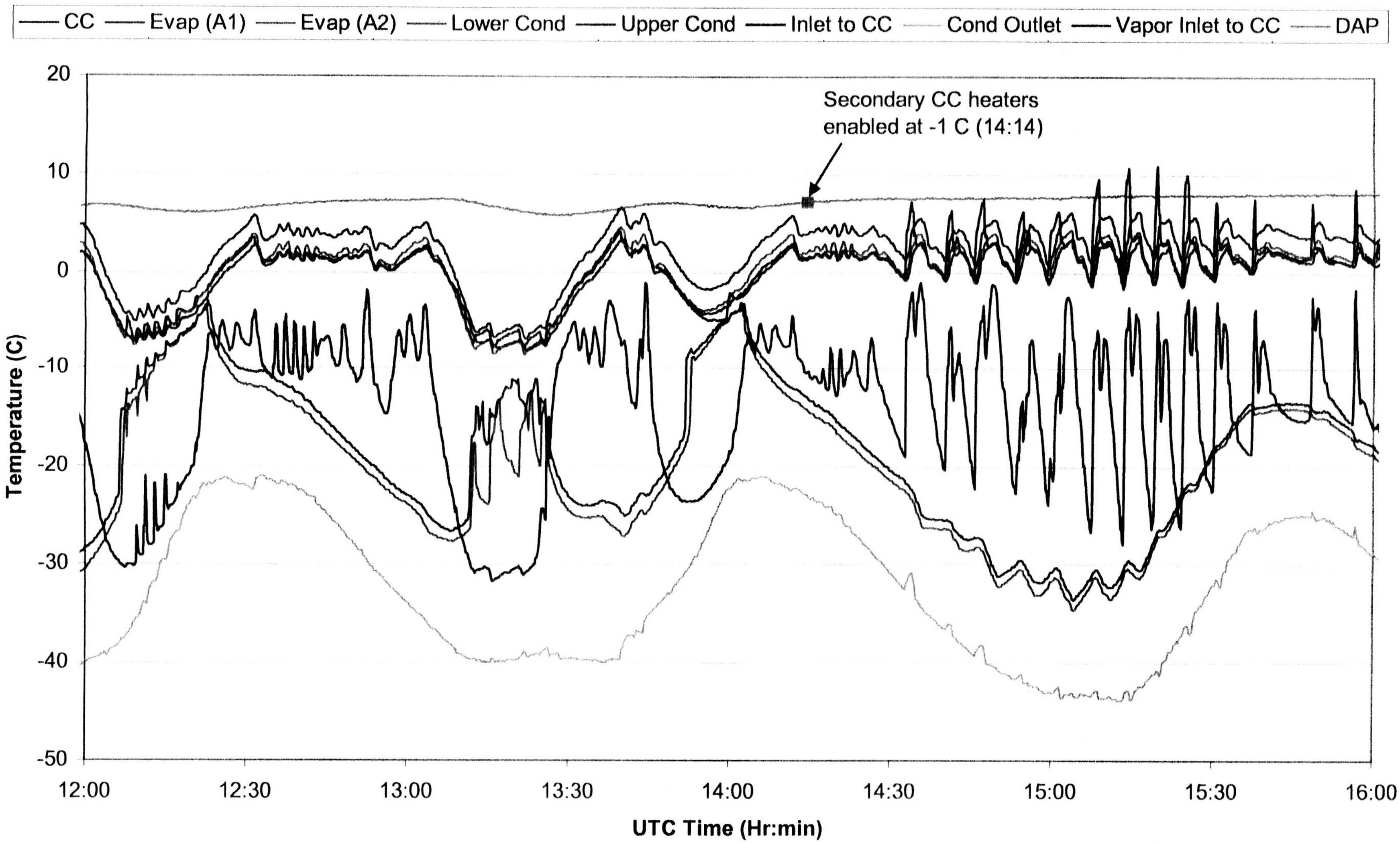
BAT Flight Data Loop 0 Day 332 (11/27/04)
Cold Shocks



Loop 0 Cold Shocks, continued

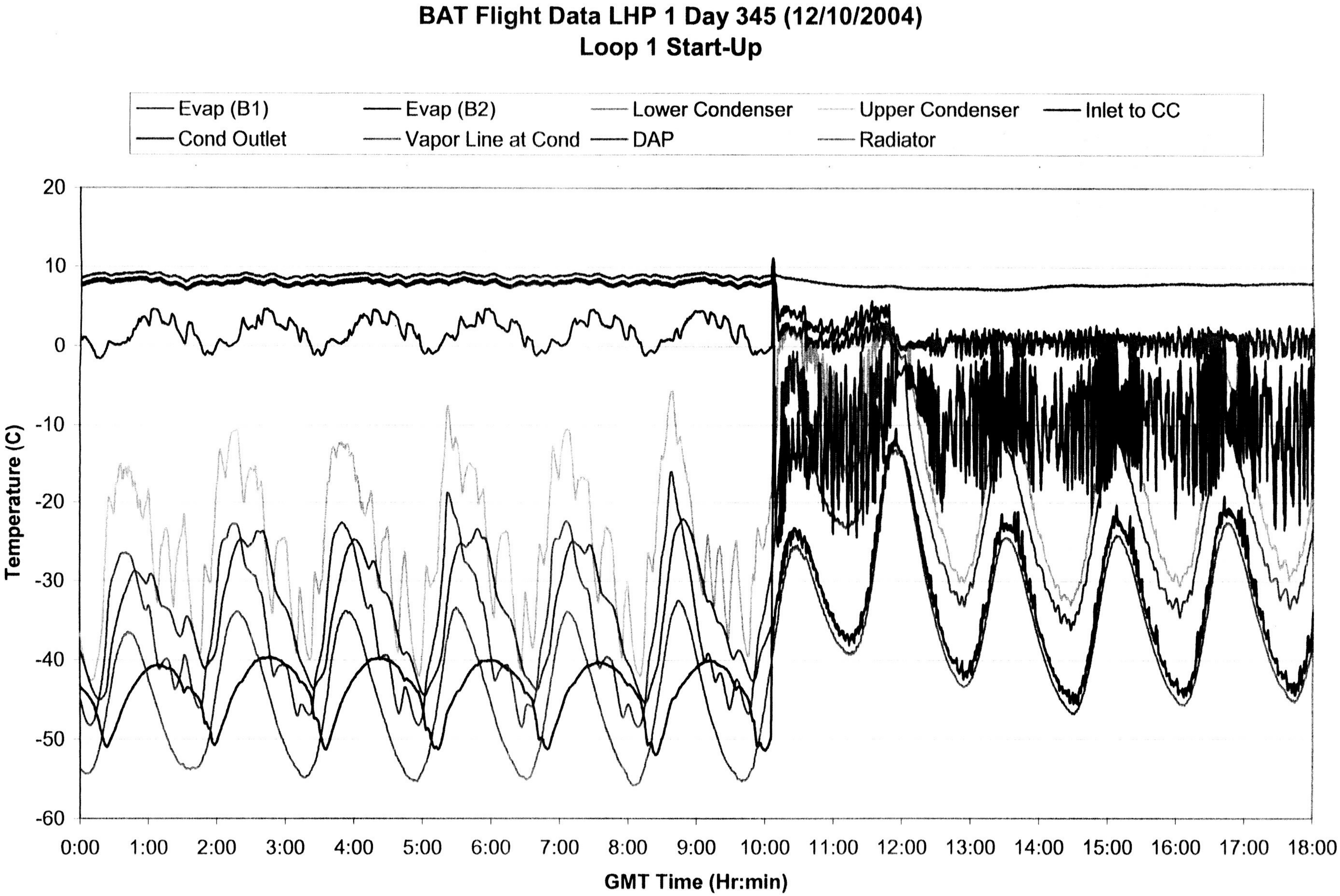
- Cold Shocks undesirable for several reasons
  - DAP temperature is not being maintained within specs during cold shocking
  - Survival heater thermostats are not designed or intended to cycle rapidly throughout the mission – reliability issues
- Decision was made to enable secondary CC heaters to try to lower magnitude of cold shocks and try to avoid having survival heaters cycle on
- Secondary CC heaters enabled and set 1 °C below the primary heaters on 12/2/04
  - Although overall LHP stability appeared to get worse, stability of DAP improved
  - In addition, survival heaters no longer cycling on
  - This configuration was deemed an improvement, although some tweaking was done to CC heater set points to attempt to damp oscillations

BAT Flight Data Loop 0 Day 337 (12/2/04)
Cold Shocking and Response to Number of CC Heaters Enabled



Loop 1 Start-up

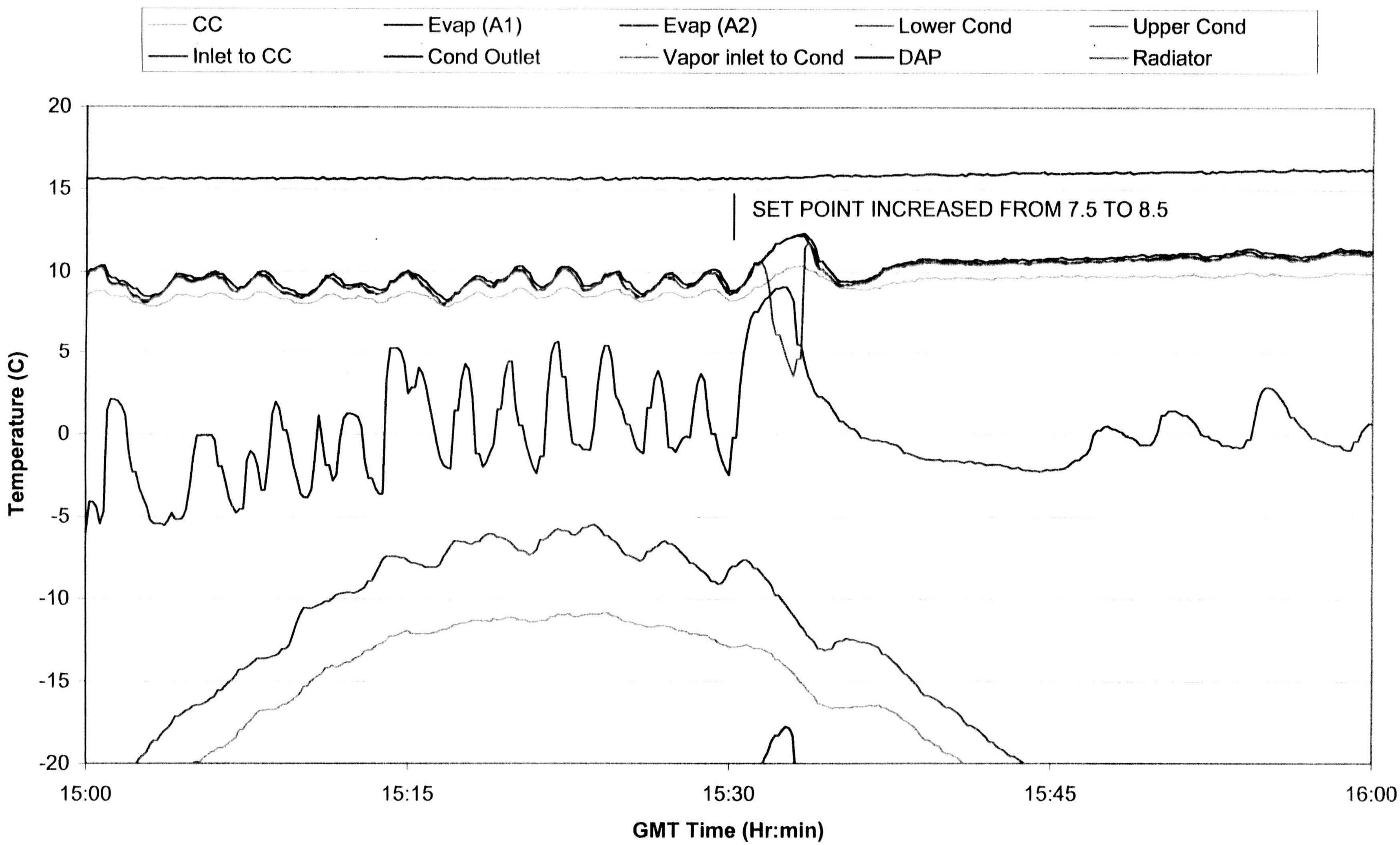
- Loop 1 start up procedure began on day 344 (12/9/04)
- Primary CC heater set point lowered from 10 to 0 °C.
  - Despite cold bias, CC temperature only dropped to temperature of DAP (around 6 °C)
- After about 9 hours, secondary CC heater activated and set to -2.5 C (didn't come on, as temperatures were well above this)
- Starter heater (60 W) activated on day 345
  - Loop started within 2 minutes
  - Vapor reached condenser immediately at start-up
  - Super heat in evaporator about 3 °C
  - Temperatures of DAP dropped after start-up as temperature gradient improved with both loops operating


BAT Flight Data LHP 1 Day 345 (12/10/2004)
Loop 1 Start-Up
Evap (B1)
Evap (B2)
Lower Condenser
Upper Condenser
Inlet to CC
Cond Outlet
Vapor Line at Cond
DAP
Radiator
20
10
0
-10
-20
-30
-40
-50
-60
Temperature (C)
0:00
1:00
2:00
3:00
4:00
5:00
6:00
7:00
8:00
9:00
10:00
11:00
12:00
13:00
14:00
15:00
16:00
17:00
18:00
GMT Time (Hr:min)

Set Point Temperature Increase

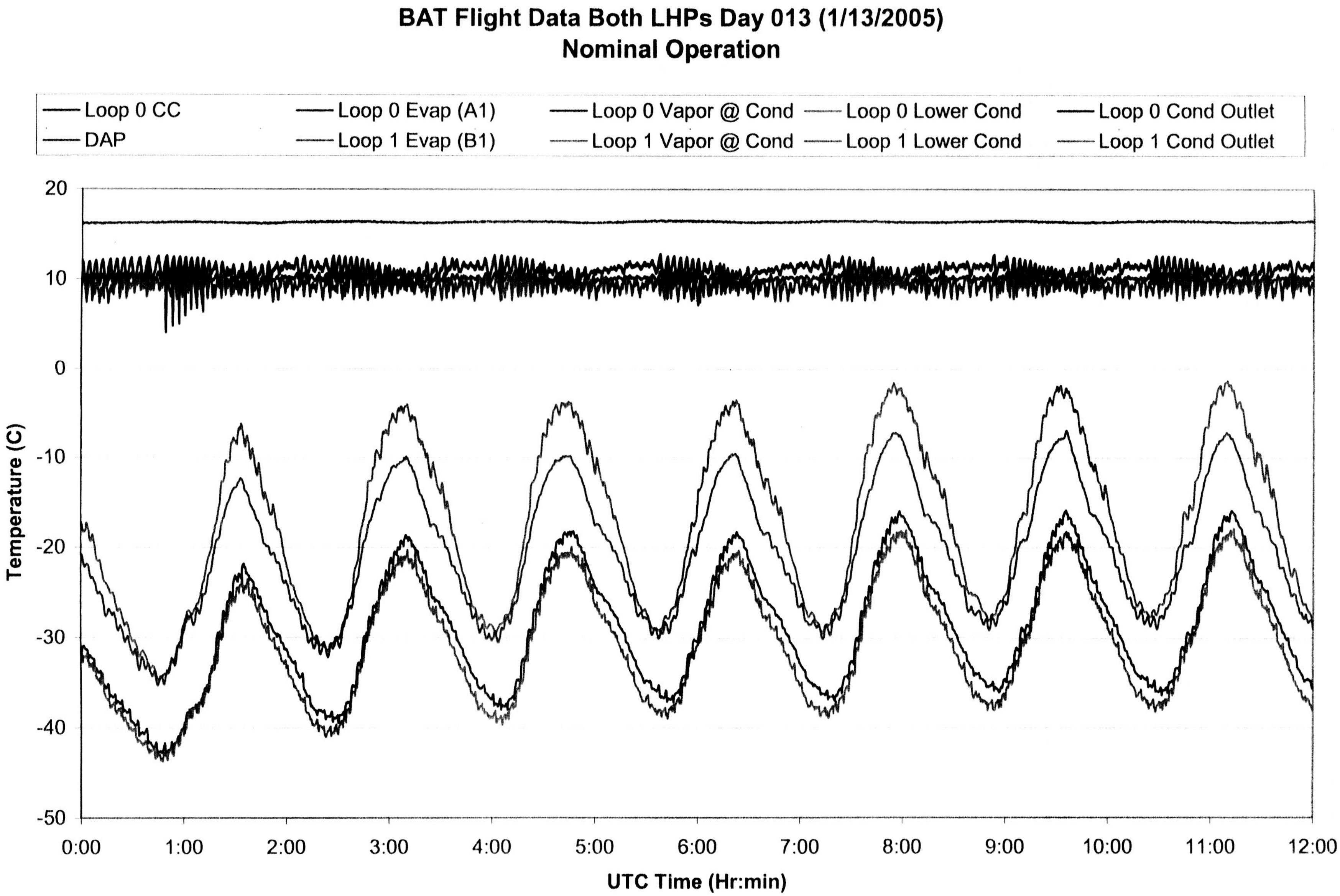
- After both LHPs were running and instrument was fully operational, LHP saturation temperature was increased to bring detectors to their desired operating temperature of 20 °C
- Set point temperature of both loops was increased (at same time) in approximately 1 °C increments
  - Set point increased from 0 °C to 8.5 °C over two days
  - Greater increments in ground testing had shut down one of the LHPs
- Temperature drop in condenser inlet sensor indicates that loop does temporarily stall during most set point increases

BAT Flight Data Loop 0 Day 347 (12/12/04)
Set Point Increase



Current Operation

- Detector blocks are maintained within a delta T of 0.38 °C
- Temperature oscillations are present in both loops, but are within requirements for detector blocks
- Vapor is barely penetrating condenser and during cold portions of cold orbits, liquid is present at the inlet to the condenser
- Spacecraft slews often, with no noticeable effect on LHP operation


BAT Flight Data Both LHPs Day 013 (1/13/2005)
Nominal Operation
Loop 0 CC
DAP
Loop 0 Evap (A1)
Loop 1 Evap (B1)
Loop 0 Vapor @ Cond
Loop 1 Vapor @ Cond
Loop 0 Lower Cond
Loop 1 Lower Cond
Loop 0 Cond Outlet
Loop 1 Cond Outlet
20
10
0
-10
-20
-30
-40
-50
Temperature (C)
0:00
1:00
2:00
3:00
4:00
5:00
6:00
7:00
8:00
9:00
10:00
11:00
12:00
UTC Time (Hr:min)

Conclusions

- Overall, system works well within design constraints, however,
  - CC may require more power to maintain saturation temperature, especially with only one loop operating (higher power on loop)
  - VCHP does not respond rapidly to changes in loop conditions, resulting in oscillations in system temperature
- Flight results verify that multiple LHPs can be used to control a single instrument to maintain a tight temperature